Freeway Traffic Jam Mitigation via Connected Automated Vehicles

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***Abstract*—We consider the problem of altruistic control of connected automated vehicles (CAVs) on multi-lane highways to mitigate phantom traffic jams resulting from car-following dynamics of human-driven vehicles (HDVs). In most of the existing studies on CAVs in multi-lane settings, vehicle controller design philosophy is based on a selfish driving strategy that exclusively addresses the ego vehicle objectives. To improve overall traffic smoothness, we propose an altruistic control strategy for CAVs that aims to maximize the driving comfort and traffic efficiency of both the ego vehicle and surrounding HDVs. We formulate the problem of altruistic control under a model predictive control (MPC) framework to optimize acceleration and lane change sequences of CAVs. Simulation results demonstrate significant improvements in traffic flow via altruistic CAV actions over selfish strategies.**

***Index Terms*– altruistic control, multi-lane highway, model predictive control, connected automated vehicles.**

I. Research Question and Overview

A. Research Question

Consider a multi-lane highway with a mixed autonomy traffic containing both connected automated vehicles (CAVs) and human-driven vehicles (HDVs), as shown in Fig. 1. We assume that each CAV obtains position and speed information of its surrounding HDVs via on-board sensors [1]. Moreover, CAVs exchange locally observed vehicle information with one another in the communication range for the purpose of cooperative sensing and proactive trajectory planning [2]. In this scenario, the goal of each CAV is to determine optimal sequences of acceleration inputs and lane change decisions in an altruistic fashion such that traffic objectives of *all observable vehicles* (not only the ego vehicle) are maximized under certain physical constraints. Here, lane changing can be interpreted as a high-level strategic decision [3], while acceleration control ensures traffic smoothness on the current driving lane [4], [5].

We address the question of *how altruistic driving of CAVs can affect traffic smoothness* (i.e., driving comfort and efficiency) on multi-lane roads and investigate the impact on attenuation of stop-and-go waves. We propose a model predictive control (MPC) based optimization approach to design altruistic driving strategies and incorporate the optimal velocity with relative velocity (OVRV) car-following model [6] into our framework to predict future trajectories of HDVs.

B. Overview of State-of-the-Art

In the literature, automated driving on multi-lane highways has usually been studied with an emphasis on the objectives of the host vehicle (i.e., CAVs) [3], [7], [8], ignoring the traffic-smoothing capabilities of CAVs [5]. In [7], a driving strategy on multi-lane roads is proposed to increase the efficiency, comfort and safety of the host vehicle by optimization of acceleration and lane changes in an MPC framework. However, the work in [7] does not consider the objectives of the surrounding vehicles (i.e., selfish driving) and the impact of lane changing on attenuation of jamming waves. In [8], an MPC-based mixed-integer quadratic programming problem is formulated to optimize longitudinal velocity and lane change maneuvers of the host vehicle. As another example of selfish driving, the study in [3] develops a multi-agent reinforcement learning (RL) framework to achieve coordination among multiple automated vehicles on highways.

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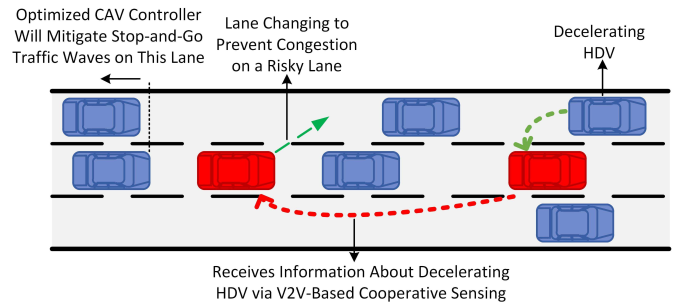

Fig. 1. Exemplary multi-lane highway scenario with CAVs (red) and HDVs (blue) where altruistic driving decisions of CAVs can help mitigate traffic jams and improve traffic smoothness.

Altruistic driving has been considered only recently in several studies [9], [10]. In [9], a cooperative altruistic driving strategy is developed to resolve traffic deadlocks on highways by forming a coordination group via vehicle-to-vehicle (V2V) communications among CAVs. The work in [10] provides a game-theoretic analysis of altruistic autonomy from a routing perspective and investigates its effect on traffic latency under varying degrees of altruism of CAVs. To the best of authors' knowledge, this is the first study to design altruistic CAV controllers on multi-lane roads covering the objectives of both CAVs and surrounding HDVs. Our insight is that altruistic lane change decisions of CAVs can help dissipate congestion waves and improve comfort and efficiency, as depicted in Fig. 1.

II. Method

We formulate an MPC based optimization problem with the objectives of traffic efficiency and driving comfort. Traffic efficiency can be defined as the problem of maintaining a desired velocity V^* for the ith CAV (the ego vehicle) and the observable HDVs:

$$\sum_{n=1}^{N_{\rm p}} \left[(v_{i,k+n}^{\rm CAV} - V^*)^2 + \kappa \sum_{j \in \mathcal{I}_{i,k}^{\rm HDV}} (v_{j,k+n}^{\rm HDV} - V^*)^2 \right] \qquad (1)$$

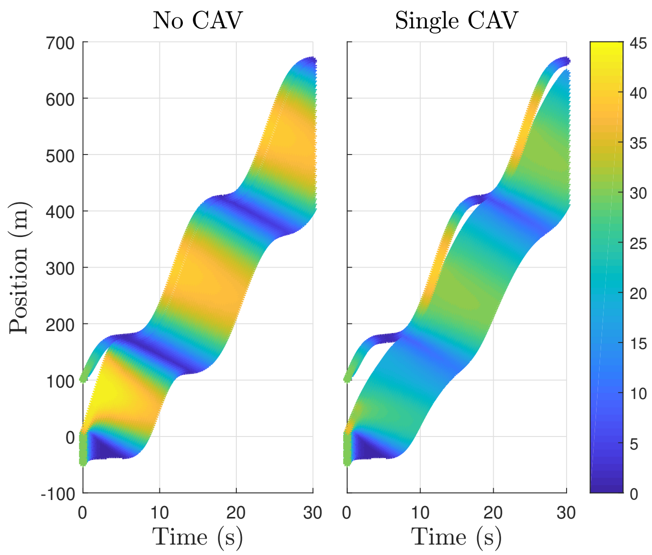

Fig. 2. Spatio-temporal evolution of velocities $(\mathrm{m/s})$ of 30 vehicles on a single-lane road where the leading vehicle creates sinusoidal perturbations to mimic the impact of stop-and-go waves. On the left scenario, all vehicles are HDV, while on the right scenario, the third vehicle is a CAV whose acceleration is determined by the optimal solution of the MPC problem with 8 s prediction horizon.

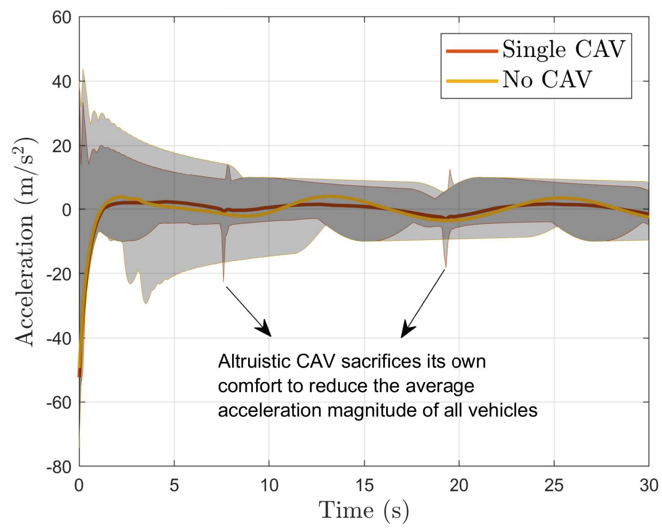

Fig. 3. Accelerations corresponding to average (colored lines) and max-min (gray shaded areas) values for the cases of no CAV and single CAV, as illustrated in Fig. 2.

where k denotes the current discrete-time index, N_p is prediction horizon, $v_{i,k}^{\mathrm{CAV}}$ and $v_{j,k}^{\mathrm{HDV}}$ represent, respectively, the velocities of the ith CAV and jth HDV, $\mathcal{I}_{i,k}^{\mathrm{HDV}}$ is the set of HDVs observed by the ith CAV, and κ is a constant factor that represents the *level of altruism* [10], i.e., how much CAV prioritizes the surrounding traffic with respect to its own driving objectives. Driving comfort is related to the magnitude of accelerations

$$\sum_{n=1}^{N_\mathrm{p}} \left[\left(a_{i,k+n}^{\mathrm{CAV}}\right)^2 + \kappa \sum_{j\in\mathcal{I}_{i,k}^{\mathrm{HDV}}} \left(a_{j,k+n}^{\mathrm{HDV}}\right)^2 \right] \tag{2}$$

where $a_{i,k}^{\mathrm{CAV}}$ and $a_{j,k}^{\mathrm{HDV}}$ represent, respectively, the accelerations of the ith CAV and jth HDV. Since HDV acceleration is a function of the position and speed of the preceding vehicle due to the car-following behavior [6], the effect of CAV control actions can be propagated upstream towards HDVs moving on the same lane and affect the traffic objectives in (1) and (2).

III. Analysis and Results

Given a fixed lane change sequence, the MPC problem in Sec. II can be expressed as convex quadratic program with linear constraints. Hence, the overall control problem can be solved by solving multiple low-level acceleration control problems corresponding to different lane change sequences and combining the results to reach the optimal high-level lane change decisions. Fig. 2 and Fig. 3 illustrate the result of optimal CAV control actions in an exemplary single-lane scenario where the leading vehicle creates continuous perturbations, leading to stop-and-go waves. We observe that even a single CAV can provide considerable improvement in traffic smoothness. The preliminary results for multi-lane roads with multiple CAVs will be presented during the conference.

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